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Fabrication of Ge nanocrystals doped silica-on-silicon waveguides and observation of their strong quantum confinement effect

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Abstract: *Standard silica-on-silicon waveguides with a core doped by Ge nanocrystals were fabricated using PECVD and RIE. Transmission of the waveguide was measured ,and strong absorption peaks at 1056.8nm, 1406nm and 1263.2nm were observed.*

1. Introduction

During the past decades, germanium (Ge) nanocrystals (nc), also called nanoclusters or quantum dots, have undergone intensive theoretical and experimental research, not only due to their unique electrical and optical properties brought by the quantum confinement effect, but also in light of the potential new devices based on these properties.Among these, Ge nc embedded in a silica matrix material have been mostly investigated for potential applications as light emitters, non-volatile optical memory and enhanced third-order optical nonlinear effects, respectively. One of the major challenges in these efforts has been a small interaction volume. For example; when characterizing Ge nc with respect to optical nonlinearity high power lasers are needed (typically hundreds of milliwatts). This is due to the small Ge nc film thickness (µm).

In this paper, we demonstrate Ge nc doped into the core of a silica waveguide. By coupling light in and out of the waveguide, the interaction length between Ge nc and light is increased by five orders of magnitude, from sub-micrometers to centimetres, which not only relaxes the requirement to the power levels of a probe light source, but also eliminates thermal issues. Ge nc doped waveguides also facilitates characterization of nonlinear behaviour by the use of well established optical waveguide theory and experimental technology.

2. Experiments

The fabrication of a Ge nc doped waveguide is a combination of processing of standard waveguides and formation of Ge nc. The main steps are plasma enhanced chemical vapour deposition (PECVD) and reactive ion etching. The details of the standard waveguide fabrication and Ge nc formation can be found in [1] and [2], respectively.

Optical characterization was carried out by using a standard waveguide component characterization setup. It consists of a broadband source, a polarizer, a polarization controller (PC), and an optical spectral analyzer (OSA). The Ge nc doped waveguide was placed in a xyz 3D adjustable stage. The light was coupled in and out of the waveguides using standard fibers. An 1.2cm long Ge nc doped waveguide was measured and compared against a standard waveguide of the same length using the same setup. All measurements were made at room temperature.

3. Results and discussions

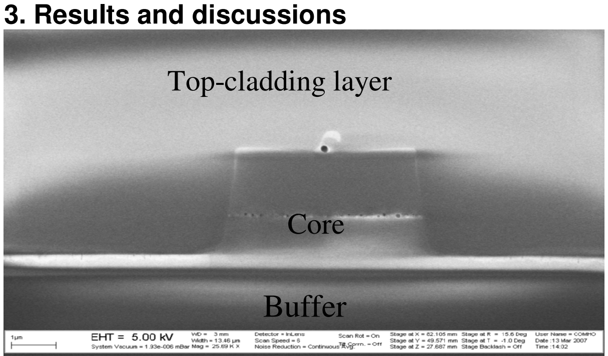

Fig. 1 (a) SEM cross-sectional image of Ge nc doped waveguide. A 3x4 μm^2 core is buried in the top-cladding and the buffer. A strip containing Ge nc is sandwiched close to the middle position of the core.

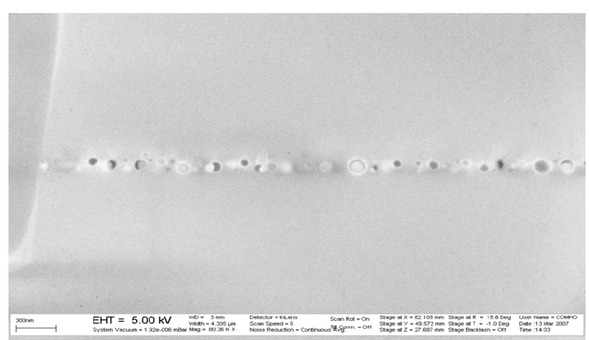

Fig. 1 (b) Zoom in of the strip containing Ge nc. The Ge nc are varied in size, and the largest one is 140nm.

The cross-section of the Ge nc doped waveguide was investigated with a scanning electron microscope (SEM), see Fig. 1. Fig. 1(a) shows that the core is buried in the buffer and top-cladding layer of the waveguide. A strip of Ge nc doped germanosilicate layer is sandwiched in the middle of the core. Fig. 1(b) is a zoom in of the area containing the

Ge nc. It is noted that the Ge nc varies in size. The maximum diameter is 140nm. It is also noted that only a very small fraction of the core is doped by Ge nc. The reason for this is to avoid an extremely high scattering loss of the waveguide due to the Ge nc. In addition, by using relatively low Ge nc concentration, the waveguide is kept single moded at dimensions similar to dimensions of standard silica-on-silicon integrated lightwave circuits. Finally, this design also has flexibility that the fraction of Ge nc in the core may be adjusted simply by adding more strips, as shown in [2].

Measured transmission spectra of a 1.2 cm long standard waveguide and a Ge nc doped waveguide of the same length are shown in Fig. 2 (a), together with output spectrum of the broad band light source. The standard waveguide has very low propagation loss, in the order of 0.02dB/cm [1]. Therefore, the total 5 dB loss is mostly caused by mode mismatch of the standard waveguide to fibers.

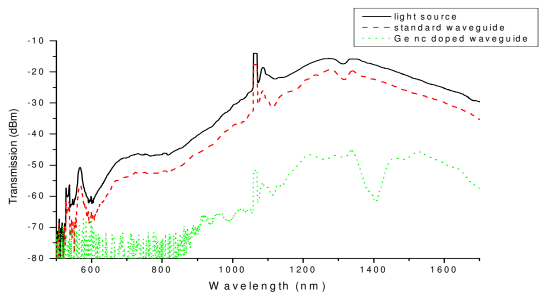

Fig. 2 (a) Spectra of the light source output (solid line), transmission of standard waveguide (dash line) and Ge nc doped waveguide (dot line)

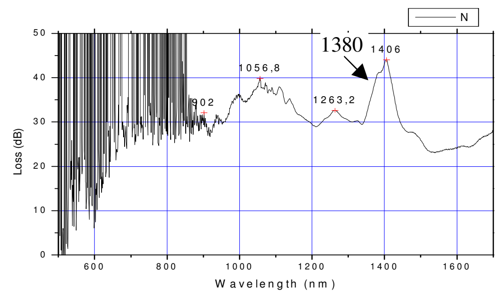

Fig.2 (b) Absorption curve of Ge nc doped waveguide

From the data in Fig. 2(a) the absorption of the Ge nc doped waveguide is obtained by subtracting the transmission spectrum of the Ge nc doped waveguide from that of the standard waveguide, shown in Fig.2(b). The resulting loss represents the pure loss due to the Ge nc, assuming that the coupling losses are the same. Fig.2(b) shows that the loss caused by Ge nc is 22 dB at 1550nm, which is 18dB/cm. At wavelengths shorter than 900nm, the waveguide is very lossy. Most important in Fig. 2(b) is the local absorption peaks. Within the wavelength range from 900nm to 1700nm, there are 3 dominant peaks located at 1056.8nm, 1263.2nm and 1406nm respectively. The peak at 1406nm is very sharp, while the 1056.8nm peak is very broad and has several satellite peaks. The peak at 1406nm is in agreement with the results obtained by Kuo et al [3], who also observed a strong exciton peak at 1408nm. In addition to this peak Kuo et al also identified a peak at 1360nm. They attributed their peaks at 1408nm and 1360nm to electron-to-heavy-hole and electron-to-light-hole transitions, respectively. It is noted that the results of Kuo et al were obtained from Ge quantum wells deposited on a silicon substrate.

The peak reported by Kuo et al, at 1408 nm corresponds to our peak at 1406nm whereas the peak reported by Kuo et al at 1360nm appears as a shoulder at 1380nm closely collocated with the strong absorption peak centered at 1408nm. Thus we attributed our peak at 1408nm and the shoulder at 1380nm to the same transitions as reported by Kuo et al. Finally, the two clear exciton peaks are observed at room temperature, which may also be explained by substantial confinement of the electron states in the Ge nc.

4. Conclusion

Ge nc were successfully embedded in a 140nm thick strip, located in the center of a $3x4\mu m^2$ core of silica-on-silicon waveguides by using standard processing of PECVD and RIE. An absorption spectrum of the Ge nc doped waveguide is obtained using standard fibers coupled to a broadband light source. Even at room temperature, three strong absorption peaks at 1406nm, 1263.2nm and 1056.8nm were observed. We assigned the strong peak at 1406nm and the shoulder at 1380nm to the electron-to-heavy-hole and electron-to-light-hole transitions respectively, due to the strong quantum confinement in the Ge nc. By doping the core of a waveguide with Ge nc a method has been demonstrated where the interaction length (1.2cm) between Ge nc and light is increased dramatically, compared against a small film thickness (140nm) which is usually used to characterize Ge nc.

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